AD-780 451

LASER DIAGNOSTIC TECHNIQUES AT POLY-
TECHNIC INSTITUTE OF NEW YORK AERO-
SPACE FACILITIES

S. Lederman, et al

Polytechnic Institute of New York

AD- 78 0 451

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER PINY-AE/AM Report No. 74-8	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) LASER DIAGNOSTIC TECHNIQUES AT POLYTECHNIC INSTITUTE OF NEW YORK AEROSPACE FACILITIES		5. TYPE OF REPORT & PERIOD COVERED Interim
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) S. Lederman M.H. Bloom J. Bornstein P.K. Khosla		8. CONTRACT OR GRANT NUMBER(s) N00014-67-A-0226-0005 & DAHC04-69-C-0077
9. PERFORMING ORGANIZATION NAME AND ADDRESS Polytechnic Institute of New York Route 110 Farmingdale, New York 11735		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Project NR-098-038 & Program Code 62301E
11. CONTROLLING OFFICE NAME AND ADDRESS Off. of Naval Research Advanced Research Dept. of the Navy Projects Agency Arlington, VA 22217 Arlington, VA 22209		12. REPORT DATE May 1974
		13. NUMBER OF PAGES 31
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) Purdue University U.S. Army Research Project SQUID Office West Lafayette, IN Box CM, Duke Sta. 47907 Durham, NC 27706		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Raman spectroscopy
Laser Doppler anemometry
Concentration measurements
Temperature measurements

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A short discussion of some conventional diagnostic techniques, followed by a discussion of the Raman effect and the laser Doppler anemometer, is given. The apparatus used at PINY and the techniques developed utilizing the Raman effect are described. Some experimental results concerning concentrations of mixtures and temperature measurements in flames are presented and discussed.

DD ₁ FORM ₇₃ 1473   EDITION OF 1 NOV 65 IS OBSOLETE

LASER DIAGNOSTIC TECHNIQUES AT

POLYTECHNIC INSTITUTE OF NEW YORK AEROSPACE FACILITIES

by

S. Lederman, M. H. Bloom,

J. Bornstein, and P. K. Khosla

POLYTECHNIC INSTITUTE OF NEW YORK

Department

of

Aerospace Engineering and Applied Mechanics

May 1974

PINY-AE/AM Report No. 74-8

LASER DIAGNOSTIC TECHNIQUES AT
POLYTECHNIC INSTITUTE OF NEW YORK AEROSPACE FACILITIES[†]

by

S. Lederman,[‡] M. H. Bloom,[*]

J. Bornstein,[**] and P. K. Khosla[+]

Polytechnic Institute of New York
Preston R. Bassett Research Laboratory
Farmingdale, New York

ABSTRACT

A short discussion of some conventional diagnostic techniques, followed by a discussion of the Raman effect and the laser Doppler anemometer, is given. The apparatus used at PINY and the techniques developed utilizing the Raman effect are described. Some experimental results concerning concentrations of mixtures and temperature measurements in flames are presented and discussed.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF SYMBOLS

A	complex electric field amplitude of the incident wave
a	particle diameter
C_1	constant
c	velocity of light
D	beam diameter
d	diameter of Airy disc
E	transition probability
f	focal length
f_d	Doppler frequency
f_o	incident frequency
κ	Boltzmann's constant
k_o, k_s	unit vectors in the incident and scattered directions
M_1	induced dipole moment
N	number of scatterers
T	temperature
α'	isotropic part of the change of the polarizability
v'	anisotropic part of the change of the polarizability
λ	wavelength
v	wave number
χ	fraction of the anisotropic scattering

Subscripts

A	Anti-Stokes
k,n,r	energy levels
S	Stokes
o	incident

I. INTRODUCTION

With the modern development in aeronautical sciences a major
effort has been directed at the problem of obtaining meaningful
measurements in the ground-based experimental facilities. As is
well-known, some of the problems of diagnostics of flow fields
have been studied since the inception of the science of fluid
dynamics. As a result of these efforts, some very sophisticated
techniques have been developed. Some of these techniques became
standard in the field. The optical techniques such as schlieren,
shadow, interferometry and holography are capable of providing
excellent qualitative insights into some flow fields. While there
are a number of methods which permit the extraction of quantita-
tive density data from the above techniques, they are generally
extremely complicated, time-consuming, expensive, and prone to too
many errors to be of any practical importance. The general
applicability of the above techniques is limited by the short-
comings of all diagnostic techniques which depend on the index
of refraction.

Other techniques such as the electron beam fluorescence
technique, emission and abosrption techniques, while capable of
providing quantitative data, have limitations on their range of
applicability or resolution.

Probe techniques, such as pressure temperature, heat transfer,
hot wire anemometer, chromatography, etc., can provide excellent
quantitative information on the parameters of a given flow field.
However, the mere presence of a probe may alter the given flow field
and distort the information one is seeking. Moreover, in some

1

cases, the ambient conditions in the flow may preclude the use of probes. Extremely high temperatures, pressures, and particulates present in a flow may be highly destructive for any probe.

In view of the above, a search for a measuring technique which could overcome most of the limitations and shortcomings of the standard diagnostics was undertaken.

As is well-known, an ideal measuring technique would permit the attainment of most information, remotely, without disturbing probes, instantaneously and simultaneously.

This we believe can be achieved by the use of the Raman effect. It has been shown[1] that it is possible not only to obtain individual specie concentration measurements in gas mixtures, but also to obtain measurements of specie concentration[2] under adverse ambient conditions which would make other measurement impossible. Furthermore, it was shown[3] that it is possible to apply this method to the remote measurement of pollutants in the atmosphere. This diagnostic technique proved itself to be very effective in the measurements of concentration in an isothermal, low speed turbulent jet and in a methane CO_2 flame[4].

After a short discussion of some deficiencies of some standard diagnostic techniques, the advantages and limitations of the Raman diagnostic technique is reviewed. Some laboratory arrangements for a number of experimental investigations relating to the applicability of the Raman effect for fluid dynamic measurements are described. Some experimental results obtained in our laboratory are discussed.

II. THE MEASUREMENT OF DENSITY AND CONCENTRATION

The shadowgraph and schlieren give indications of the second derivative and first derivative of the density in a flow field, respectively. Their main use is, therefore, flow field visualization rather than quantitative density measurements. The interferometer, on the other hand, is a most precise instrument not only for flow visualization but also for direct indication of density variation in a flow field. There is, however, one major drawback when quantitative data are desired. While the interferometer gives a direct quantitative indication of the density changes in a flow field, these changes represent integrated values over the entire thickness of the flow field. This drawback, common also to shadowgraphs as well as to schlieren, makes the above optical methods for quantitative flow diagnostics of questionable value. Even with the most advanced microdensitometric and data processing equipment available, the best one can expect is a two-dimensional map of integrated density points.

For hypersonic tunnels where test section pressures are less than about 1 mm Hg, a density probe has been developed which uses the fluorescence produced by a narrow, well-collimated, high energy electron beam. By focusing the luminescence, which is largely confined to the electron beam region itself, onto an optical slit which is at a right angle to the beam, the light from a small gas volume is selected and can subsequently be measured through the use of a wave selector and photomultiplier. The wave selector can be a spectrograph or a narrow bandpass filter. The intensity of the light is related to the density and can therefore be used as

a direct measure of the gas density at a given point in space and in time. This kind of probe is very useful as long as the gas density is low. As the gas density increases and the time between collisions becomes comparable to the lifetimes of the excited states of the molecules, a measurable fraction of the electron beam excited molecules collide with other molecules, giving up part of their energy in a form other than radiation. This effect, known as collisional quenching, which is temperature as well as density dependent, limits the range of applicability of the electron beam density probe. It was found that for the nitrogen line 3914Å generally used in hypersonic flows, there is no quenching effect up to a test section static pressure of 100μ Hg. The applicability of the electron beam probe for density measurement has thus an upper limit of about 100μ Hg. As far as the lower limit is concerned, this would be set by the signal-to-noise ratio of the photomultipliers and associated electronic processing equipment.

The question of specie concentration measurement is generally dealt with through the application of gas chromatography. This type of measurement, which is based on the thermal conductivity of individual gases, is generally limited to a mixture of two gases. Furthermore, due to the underlying principles of this diagnostic technique, a single point measurement requires a relatively long time to perform. This technique is therefore limited to two specie mixtures in a steady state equilibrium. High frequency time varying concentration measurement cannot be obtained. A very important parameter generally required in fluid dynamic measurements is the velocity. In this respect the hot wire anemometer

4

used for the first time about 50 years ago was developed into a very sensitive and sophisticated instrument. Again, the underlying principle of operation of the hot wire is heat transfer. This instrument is capable of providing measurements from a few feet/sec. to supersonic velocities and for laminar-to-turbulence frequencies of several hundred thousand cycles. There are, however, limita-tions and shortcomings associated with this instrument. Since the sensing element is basically a heat transfer element, it is sensitive to temperature, density, viscosity, specific heat, con-ductivity, geometry, etc. This in itself makes a measurement very tedious and complicated. If one considers further the problems associated with compensating for the presence of the probe and the disturbing effects any probe may have on the flow, it is seen that it would be desirable to have a technique which would be totally or nearly independent of all these effects. In what follows, it is believed, a partial answer to the problems of density, concentration, and velocity measurements can be found.

III. LASER RAMAN AND DOPPLER MEASUREMENTS

As indicated previously, the Raman scattering technique is capable not only of supplementing the above techniques, but also of complimenting them. The theoretical background on which the Raman diagnostic technique is based has been discussed in a number of books and scientific articles[5-11]. The application of the Raman effect towards the diagnostics of flow fields is based upon the premise that most molecular species present in the flow are Raman active, and have their particular characteristic frequency shifts. At this point it is worthwhile to note that all homonuclear diatomic

5

molecules like O_2, N_2 or H_2 are infrared inactive while they are all Raman active. This is one of the very important properties of the Raman effect which makes its application to aerodynamic flow field diagnostics very useful.

The relation between the scattered radiation and the incident radiation is

$$I_{s,A} = C_1 N (v_o \pm v)^4 |E_{kn}|^2$$

where
$$E_{kn} = \frac{1}{h} \sum_v \left\{ \frac{(\bar{A}\bar{M}_{kr})\bar{M}_{rn}}{v_{rk} - v_o} + \frac{\bar{M}_{kr}(\bar{A}\bar{M}_{rn})}{v_{rn} + v_o} \right\} \tag{1}$$

In terms of the Placzek polarizability theory the scattered intensity is given by

$$\frac{I_{s,A}}{I_o} = C_2 \frac{N(v_o \mp v)^4 (\alpha'^2 + \frac{7}{45} X v'^2)}{v(1 - \exp[-\frac{hcv}{kT}])} \tag{2}$$

The ratio of the Stokes to Anti-Stokes Raman intensity is given by

$$\frac{I_s}{I_A} = \left(\frac{v_o - v}{v_o + v} \right)^4 \exp \frac{hcv}{kT} \tag{3}$$

The above equation presents the essential features of the Raman effect. With the additional feature of being extremely fast (of the order of 10^{-14} sec. for visible light illumination), it is obviously a very useful diagnostic tool for a wide variety of physical and chemical phenomena. It permits one to obtain quantitative information on the individual specie concentration, on the state of ionization, on the temperature of a given specie in a mixture at a

point in a flow field without probes and their disturbing effects.
The measure   ts can be obtained remotely, instantaneously, and
simultaneously. The number of points measured simultaneously is
only limited by the number of monitoring stations. These qualities
place this diagnostic technique on the list of ideal methods. In
reality, there are a number of difficulties encountered. One of
the major difficulties is the extremely low equivalent Raman scat-
tering cross-section. While this can partially be overcome by high
laser power and high gain photomultiplier tubes, there are limita-
tions on the minimum concentration that can be resolved. Discussions
concerning these and other features of laser Raman diagnostics are
given in Refs. 1, 2 and 4.

The combination of the laser and the Doppler law resulted in
the development of a new type of anemometer, the so-called laser
Doppler velocitimeter, LDV for short. The LDV relates the velocity
of a solid particle in a fluid (seeded or naturally present) to
the frequency shift of the scattered light from the primary fre-
quency. This frequency shift is given by

$$f_d = \frac{f_o}{c} \bar{V}(\bar{k}_s - \bar{k}_o) \ . \tag{4}$$

Although the scattering phenomenon responsible for the LDV opera-
tion is essentially given by the Mie formula (which depends upon
$\frac{\alpha}{\lambda} \gg 1$, α being the particle diameter), the frequency shift does
not depend on the size of the particulate. The LDV has been treated
in great detail in many publications too numerous to list here.

7

The LDV is essentially more a problem in data processing than in the basic operation. The velocity as measured by an LDV is essentially the velocity of a particle in a scattering volume. The scattering volume is therefore an important consideration in designing an LDV. This value is determined by the optics of the transmitter, receiver, and the size of the laser beam, and is limited by the Airy disc given by

$$d = 1.22 \frac{\lambda f}{D} \qquad (5)$$

It is therefore obvious that scattering values much smaller than hot wire anemometer probes are usually possible.

In general, compared to the hot wire anemometer, the LDV is more accurate to a wide range of velocities, is linear, independent of other velocity components in the flow, is an absolute measurement depending on the geometry, optics, and laser used. It thus does not need calibrations. It has better spatial resolution, and what is most important, it does not perturb the flow.

A basic assumption underlying the application of the LDV is that the scattering particles follow faithfully the velocity of the fluid under investigation. This, however, is not always the case. In turbulent flows at high velocity and high frequency turbulence, the particle inertia effect alone may be considerable. The velocity ratio of a particle and the flow would fall by about 10% for a particle of 1μ in diameter at a frequency of 20 kc or a particle of 3μ diameter at 2.7 kc or 10μ at 250c/sec. This points out some difficulties of an LDV. Another difficulty is the broadening of the Doppler line due to the finite residence time of the

8

scattering particle and the random distribution of scatterers.

IV. EXPERIMENTAL FACILITIES AND SOME EXPERIMENTAL RESULTS

The experimental efforts concerning laser diagnostics at PINY are manifold. They range from the experimental determination of the equivalent Raman scattering cross-section of relevant molecular species to the determination of concentration of mixtures of gases at best, the determination of concentration of particular species in jets, the measurement of temperature in flames, the determination of velocity fluctuation in a jet using an LDV, the determination of particulates in a flow, the application to pollution monitoring, and investigation of the resonant Raman effect. The basic experimental apparatus for the equivalent Raman cross-section measurement is shown in Fig. 1. This apparatus is also used for the determination of particular species in mixtures[1]. The procedure for the determination of the equivalent Raman scattering cross-section is very simple. The chamber is filled with a gas whose cross-section is known; the pressure and temperature are noted and the scattered intensity measured. The same chamber is filled with a gas of unknown cross-section and under the same conditions of pressure and temperature. The scattered intensity is again measured. From the two measurements the unknown equivalent scattering cross-section is obtained. The scattering cross-section for some species thus determined is for CO_2, $\sigma=2$ and NO, $\sigma=0.55$ referred to N_2.

Figure 2 presents the Raman intensity measurements as a

function of pressure in the chamber of a single specie and Fig. 3
presents the scattered intensity as a function of NO concentration
in water saturated nitrogen atmosphere. It should be noted here
that the measurement of NO in the presence of water is extremely
difficult using any other method. Figure 4 shows a schematic
diagram of the experimental apparatus used to obtain simultaneously
the concentration, temperature, and velocity of an axisymmetric
turbulent mixing jet and a methane CO_2 flame. This apparatus
consists of a Ruby laser of 150 mW peak power capable of single
pulse as well as repetitive operation at a pulse repetition rate
of 6 ppm, a 50 mW Jodon He-Ne laser for the LDV, spectrographs
including a Spex 1406 double-monochromator, data acquisition and
processing equipment including an on-the-line PDP8 computer and
all the necessary control equipment for the maintenance of the
given condition of the jet flow and flame. In view of the
relatively high scattering signals obtained under the experimental
conditions described here, the data acquisition equipment used
here is quite simple. The signal from the photomultiplier tube
is amplified and fed into a linear gate and hold module, where the
signal is integrated and stretched such that it can be fed into a
multiplex analog to a digital converter which is compatible with
the PDP8 digital computer. The linear gate is opened only for a
predetermined time, such that only the scattered signal is inte-
grated. The errors which may be caused by noise signals in the
photomultiplier or amplifier can thus be minimized. The data
acquisition system is capable of accepting 8 signals. One of

10

those signals is the laser signal used to trigger the gate generator, initiate the data processing cycle, and provide a normalization signal for the received signals. A schematic diagram of the data acquisition and processing system is shown in Fig. 5. Using this system specie concentration profiles on a turbulent mixing jet as well as temperature profiles of methane CO_2 flame were obtained. Some of the results are shown in Figs. 6, 7, and 8.

The LDV used in a laboratory is of the dual scatter single velocity component type. The signal is displayed on CRT frequency analyzer. At the present time, work is in progress on the assembly of a Doppler data processing system which would permit better data acquisition and the construction of a proper particle seeding system for the jet and flame.

The features of the Raman scattering diagnostic technique, as indicated above, suggests the use of this technique for remote air pollution monitoring and measuring. As shown in Ref. 3, the major drawback of this technique is the extremely small scattering cross-section and the attenuation of the signals at large distances. While short distance (below 2 km) remote, single-ended measurements of pollutants of high concentration can be easily made using the normal Raman effect, and single pulse operation large distance (over 2 km) measurements of very low pollutant concentration measurements may require not only repetitive operation of the laser with statistical data processing but also further developments in laser technology, including the application of the resonant Raman effect. To that end a research effort has been

11

initiated at PINY. As evident from Eq. (1), when the incident

frequency ν_o approaches the electronic absorption frequency ν_{rk}

of the particular molecule, a resonance occurs. Under certain

conditions the scattered intensity may increase by several orders

of magnitude. This would of course be very desirable. One could

either resolve a lower concentration or resolve the same concentra-

tion at much greater distances. There are, however, difficulties

encountered. The laser must be continuously tunable in order to

find the regions of strong resonance enhancement of the species

of interest. Once those regions are known, the incident wave-

length must be carefully controlled to maintain a precise separation

from resonance.

At resonance, the absorption of the incident light results in

fluorescence emission and not Raman scattering. While fluorescence

emission is generally very intense and characteristic of a given

molecule, collisional processes render the fluorescence emission

inapplicable for quantitative concentration measurements.

Figure 9 represents an experimental apparatus used for the

investigation of the resonant Raman effect. It is constructed to

minimize the path of the incident and scattered radiation through

the gas under investigation, thus decreasing the attenuation of

the radiation. The laser is a nitrogen laser. The gases being

investigated are the hologen gases.

V. DISCUSSION OF RESULTS

As is evident from the data in Fig. 2, the Raman scattering
technique is capable of determining the concentration of a specie
over a relatively wide dynamic range. The response in linear
with the concentration and the accuracy is in most cases adequate.
Furthermore, the data of Fig. 3 represents a measurement which is
extremely difficult to obtain by any other means. The response
is again linear independent of the presence of other species in
the mixture.

Figure 6 shows the concentration measurements of CO_2 in an
axisymmetric turbulent jet superimposed on the concentration data
obtained using a conductivity cell. At a first glance it appears
that the scatter of the data is excessive. In reality, this
scatter is an indication of the turbulent character of the flow.
This is confirmed by the data of Fig. 7, where statistical averages
50 pulses per point are plotted. These data approach the data as
obtained using conductivity cells. It must be noted that the conduc-
tivity cell used in this experiment was only capable of measuring
mean values of concentration.

Figure 8 shows the mean temperature of a methane flame as
obtained using the ratio of the Stokes to the Anti-Stokes vibrational
line. Superimposed is the temperature as obtained by a thermocouple.

13

VI. REFERENCES

1. Widhopf, G.F. and Lederman, S.: Specie Concentration Measurements Utilizing the Raman Scattering of a Laser Beam. AIAA J., 9, No. 2, pp. 309-316, February 1971.

2. Lederman, S.: Measurement of NO Concentration in Water Saturated Nitrogen. Appl. Optics, 11, No. 9, pp. 2088-2091, September 1972.

3. Lederman, S. and Bloom, M.H.: The Raman Effect and Air Pollution Measurements. J. Environ. Sys., 2(4), pp. 311-337, December 1972.

4. Lederman, S. and Bornstein, J.: Specie Concentration and Temperature Measurements in Flow Fields. Project SQUID Technical Report No. PIB-31-PU, March 1973.

5. Herzberg, G.: Molecular Spectra and Molecular Structure. D. Van Nostrand Co., Princeton, N.J., 1963.

6. Herzberg, G.: Infrared and Raman Spectra of Diatomic Molecules. D. Van Nostrand Co., Princeton, N.J., 1945.

7. Szymanski, H.A.: Raman Spectroscopy. Plenum Press, New York, 1967.

8. Placzek, G.: Rayleigh Strenung und Raman Effect. Handbuch der Radiologie Akademische, Verlag, Leipzig, 1934.

9. Bernstein, H.J. and Allen, G.: Intensity of the Raman Effect. J. Optical Soc. of Amer., 45, p. 237, 1955.

10. Stansbury, E.J., Crawford, M.F. and Welsh, H.L.: Determination of Rates of Change of Polarizability from Raman and Rayleigh Intensities. Can. J. Phys., 31, p. 954, 1953.

11. Stoicheff, B.P.: <u>High Resolution Raman Spectroscopy</u>. Vol. I,
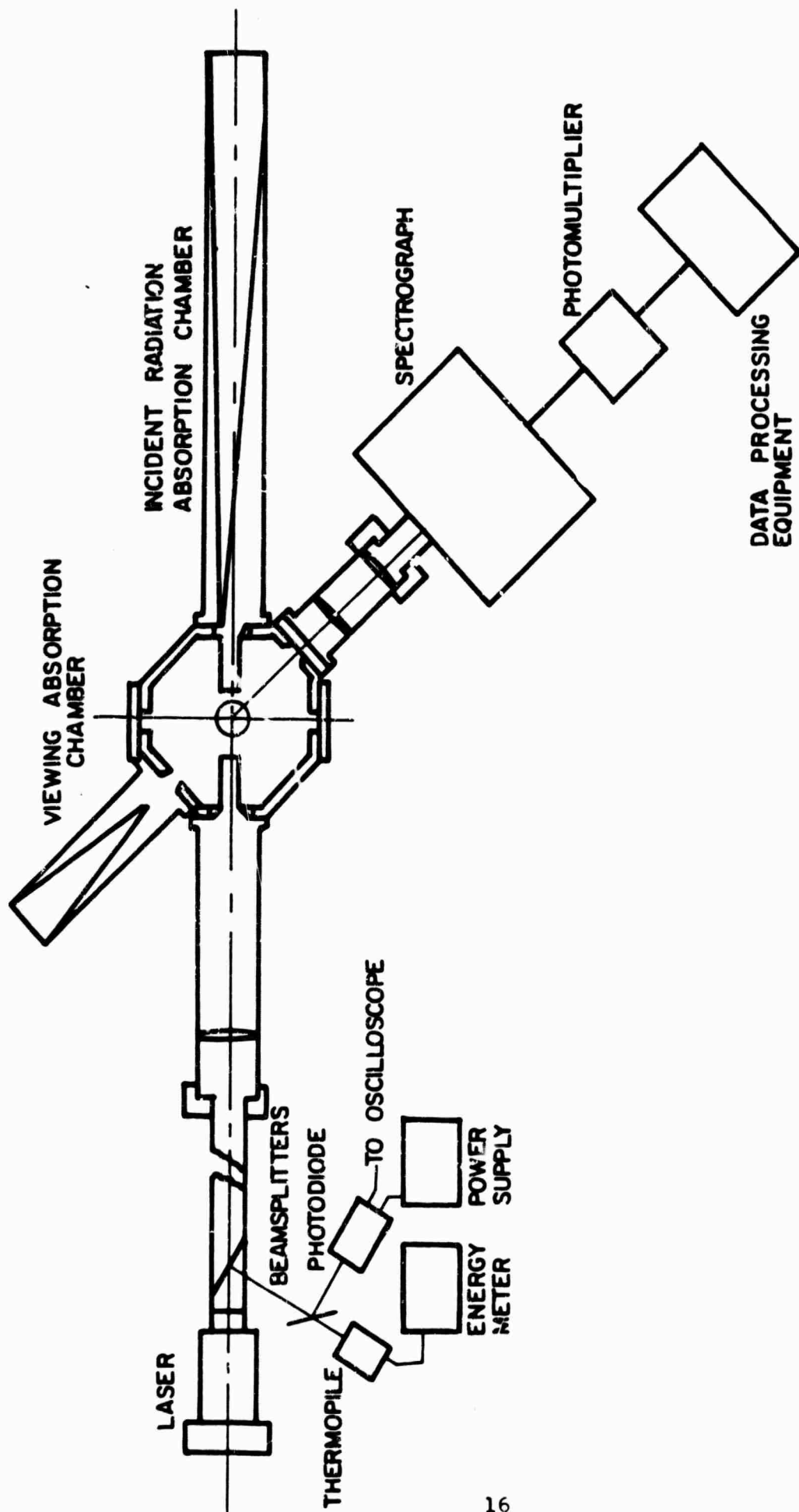
Interscience Publishers, New York, 1959.

FIG. I SCHEMATIC OF EXPERIMENTAL APPARATUS FOR RAMAN CROSS-SECTION MEASUREMENT
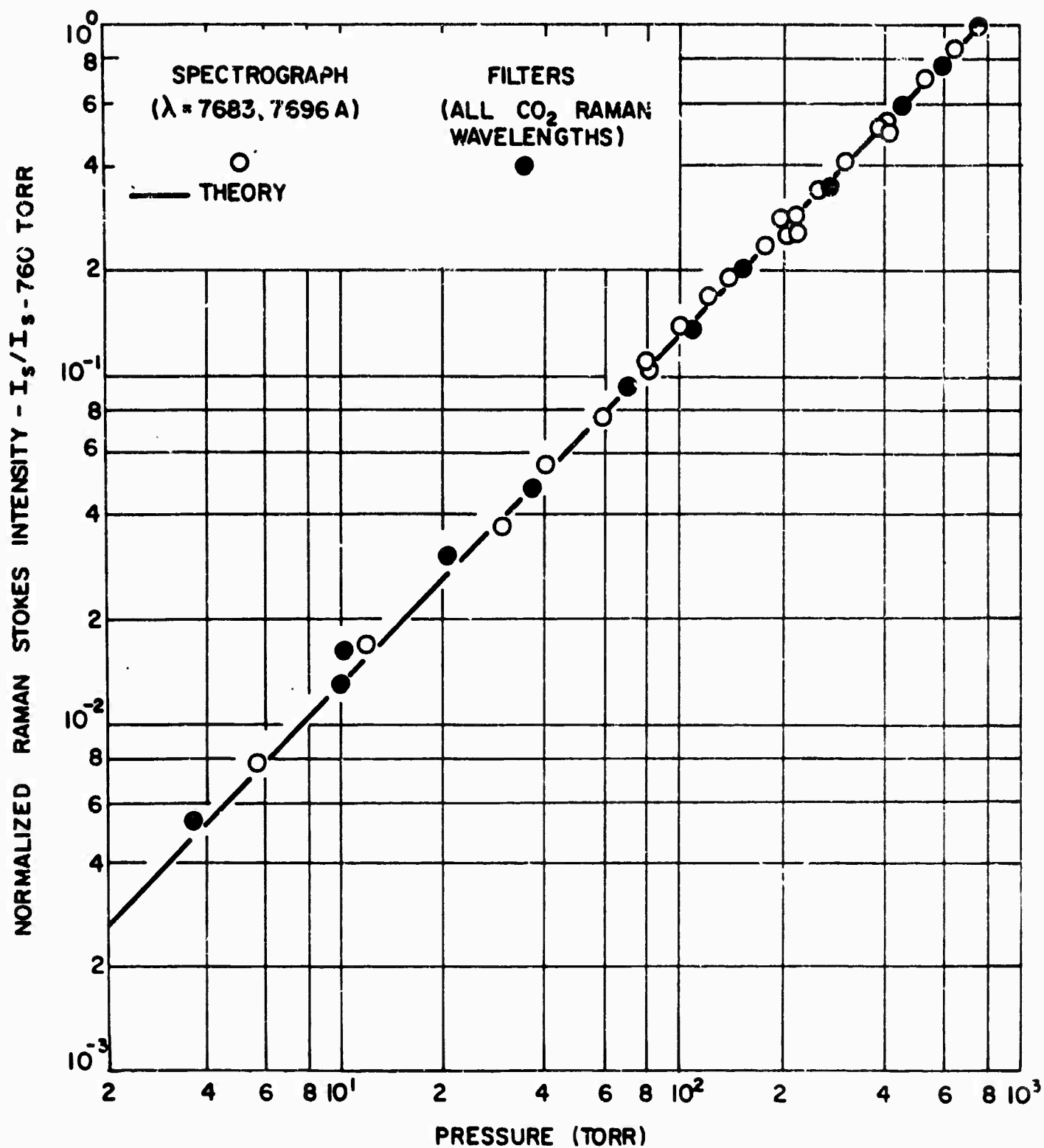
FIG. 2 MEASURED RAMAN STOKES INTENSITY OF CARBON DIOXIDE (CO_2) AS A FUNCTION OF PRESSURE. MEASURED IN AIR AT ROOM TEMPERATURE
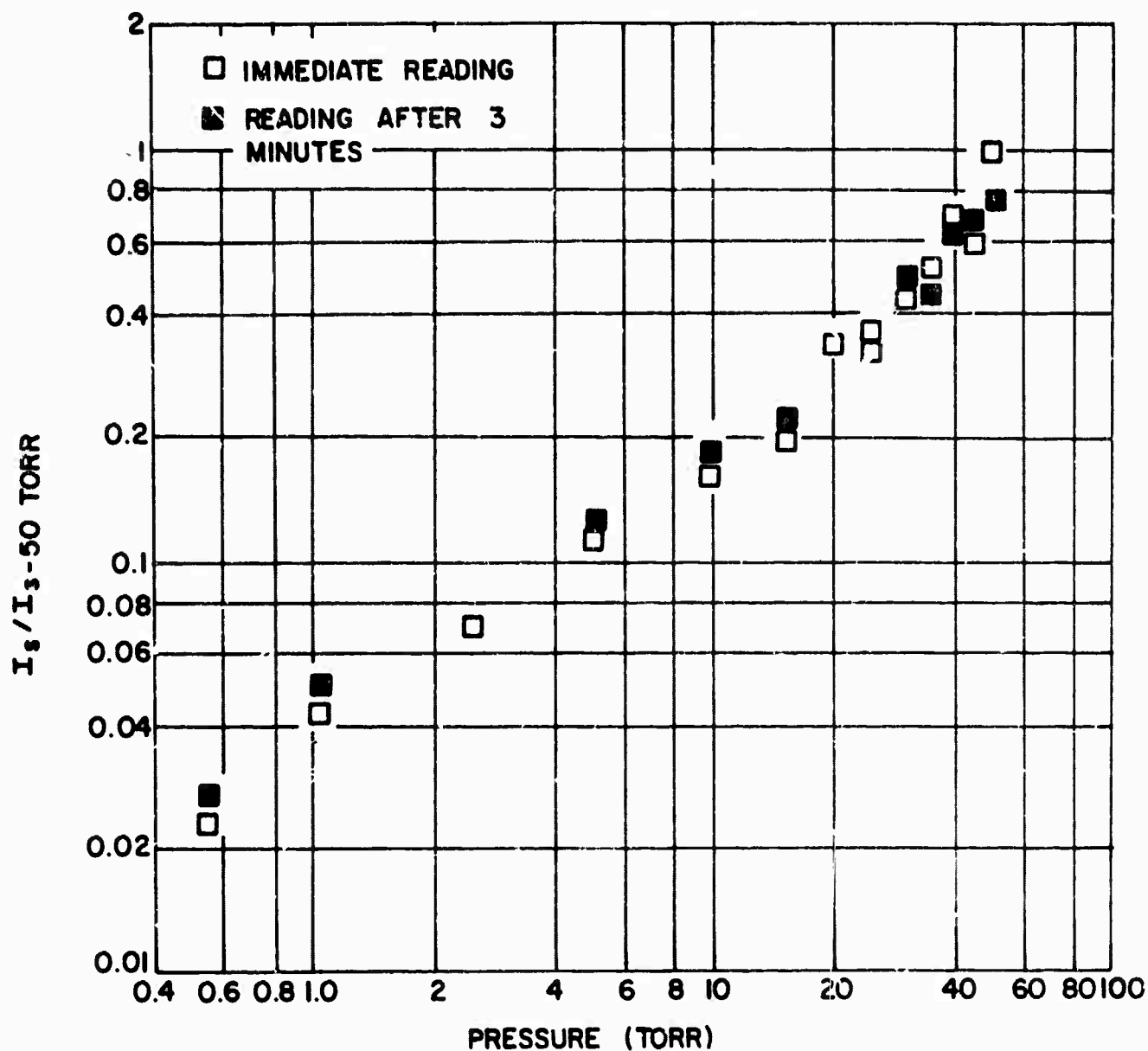
17

FIG. 3 MEASURED RAMAN STOKES INTENSITY OF <u>NO</u>
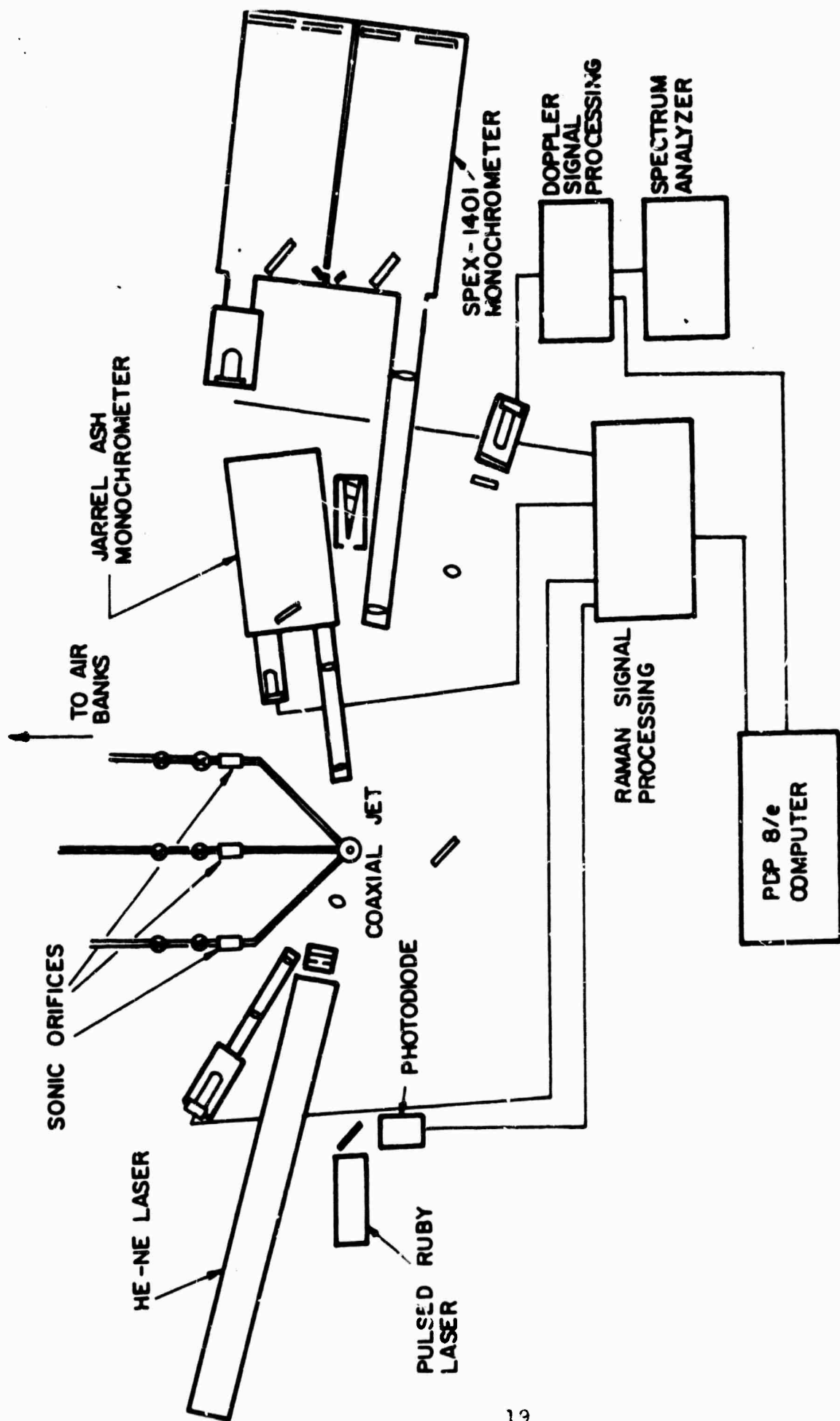IN THE PRESENCE OF WATER. SATURATED
NITROGEN VS. NO PARTIAL PRESSURE
(<u>NO</u> - NITRIC OXIDE)

18

FIG. 4 SCHEMATIC DIAGRAM OF EXPERIMENTAL APPARATUS (CO-AXIAL JET)
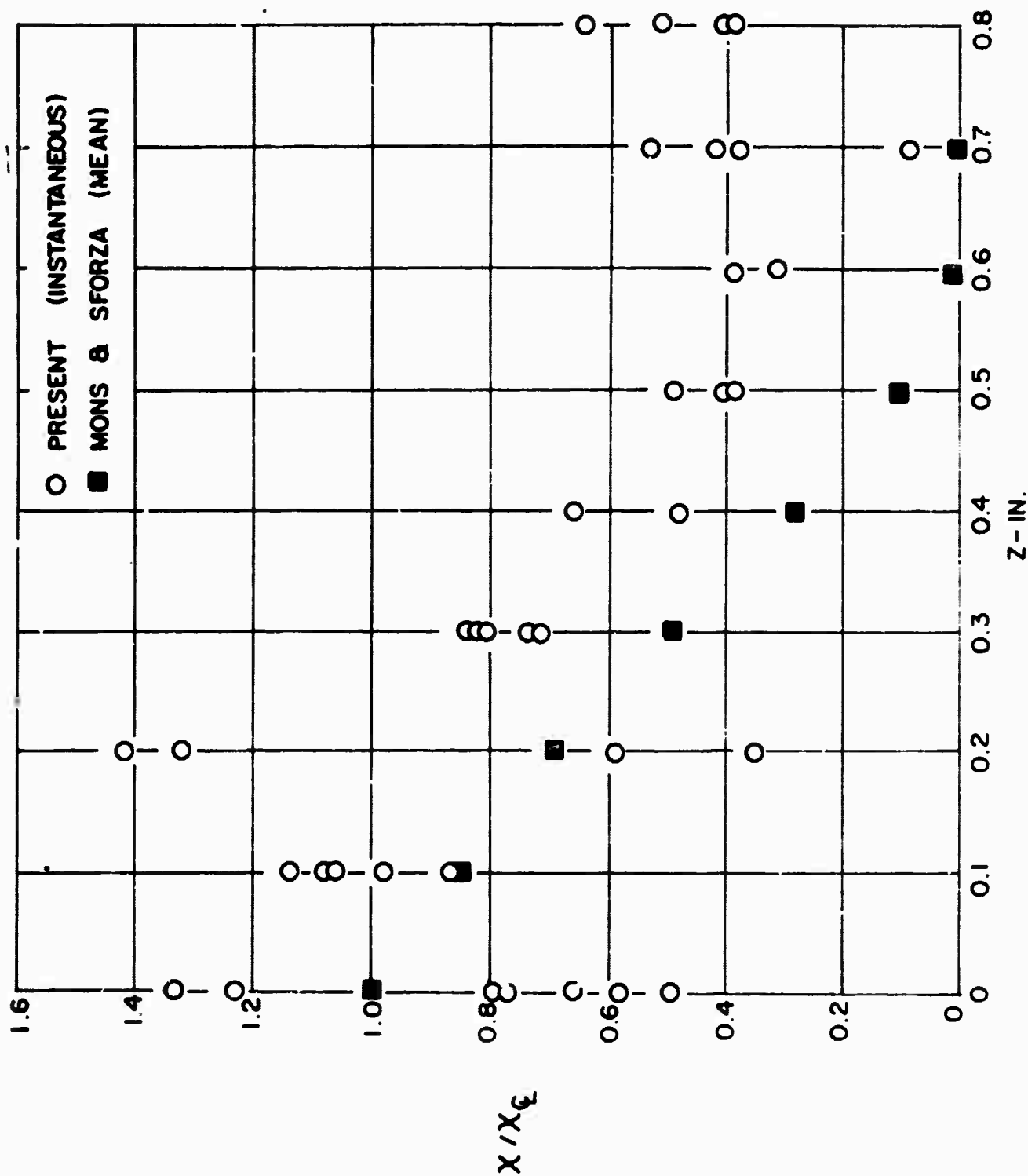
19
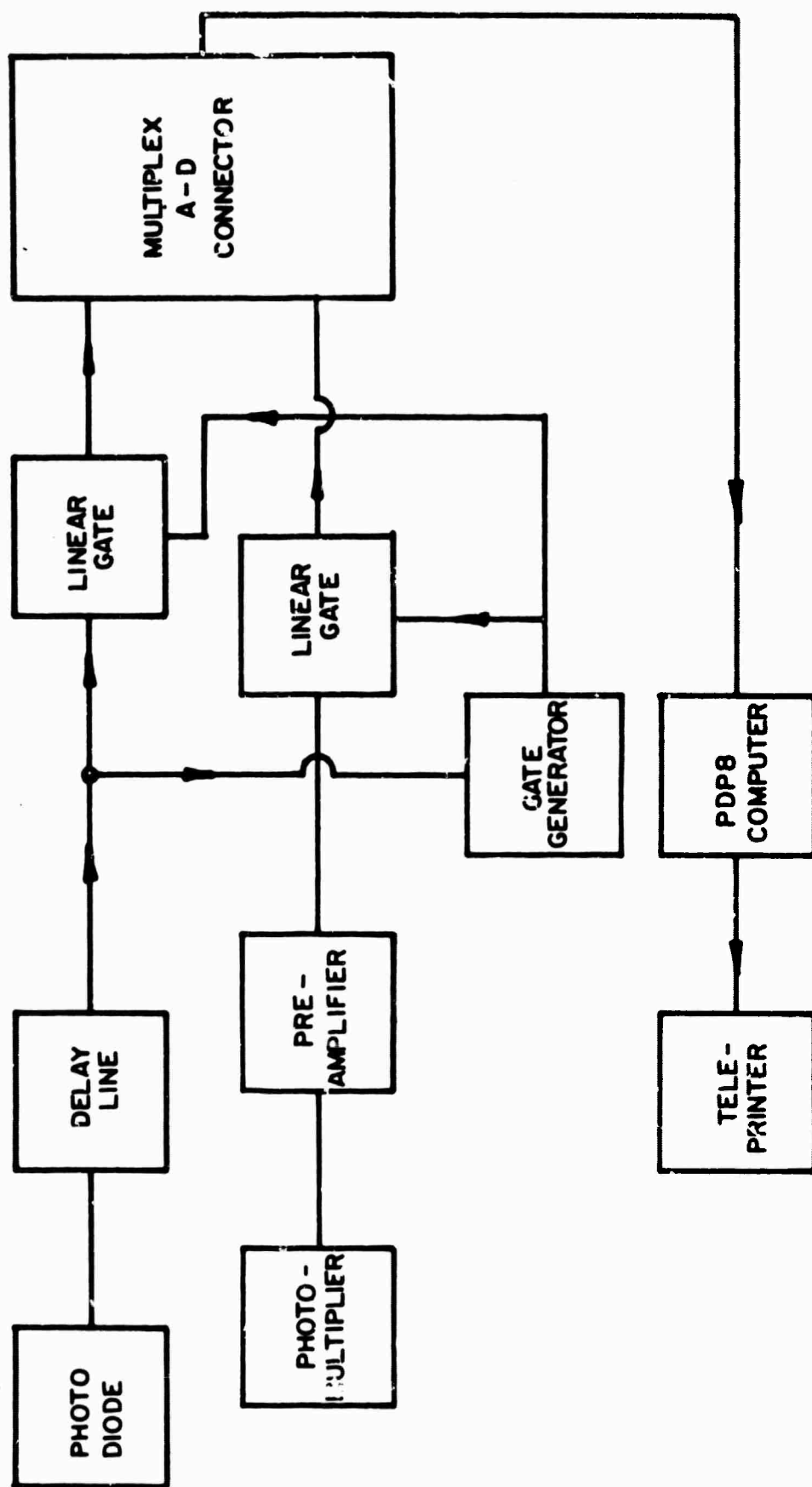
FIG. 5 DATA ACQUISITION AND PROCESSING

FIG. 6 INSTANTANEOUS SPECIE CONCENTRATION OF CO_2 IN A TURBULENT JET AT x/D = 5
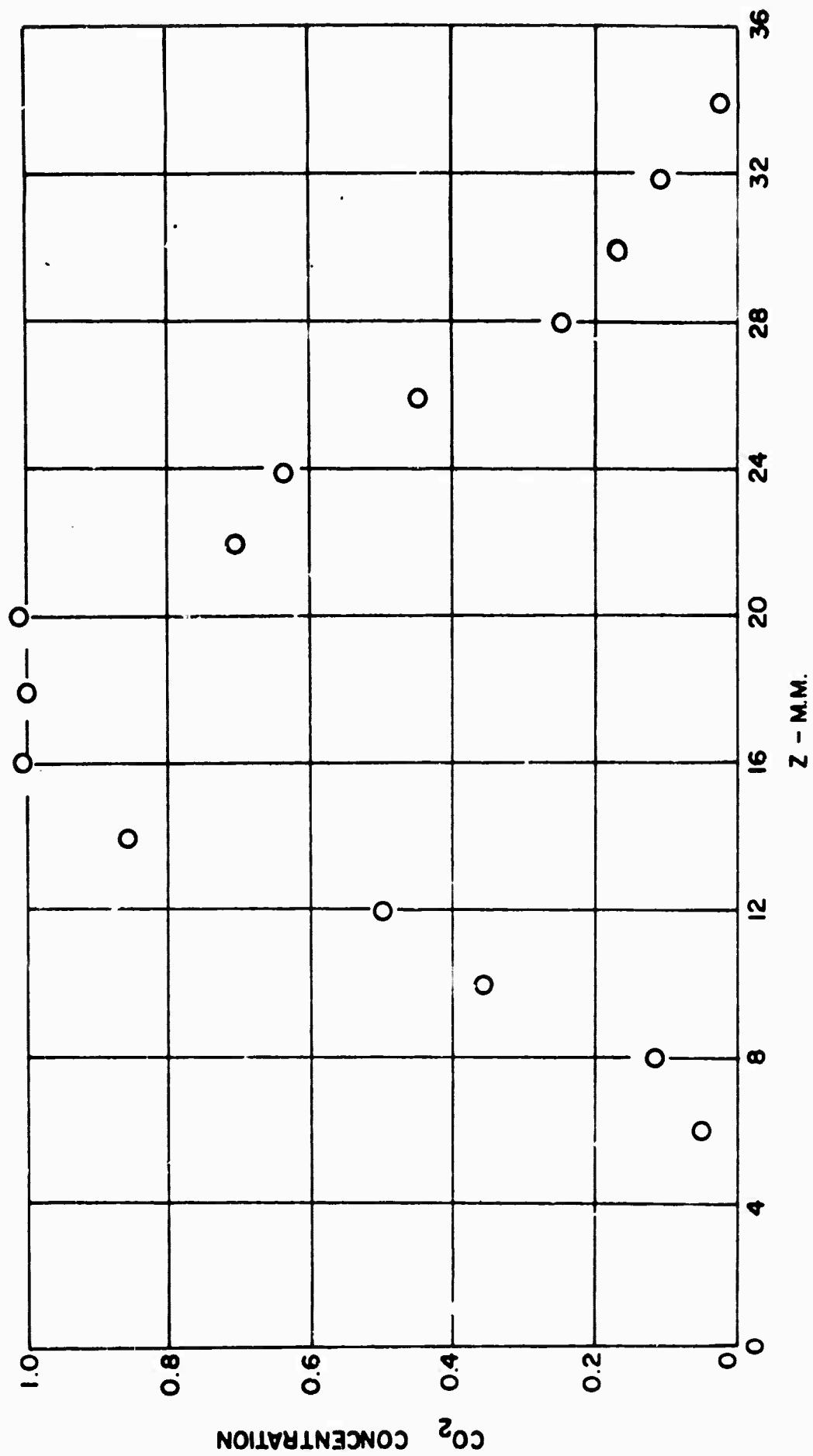
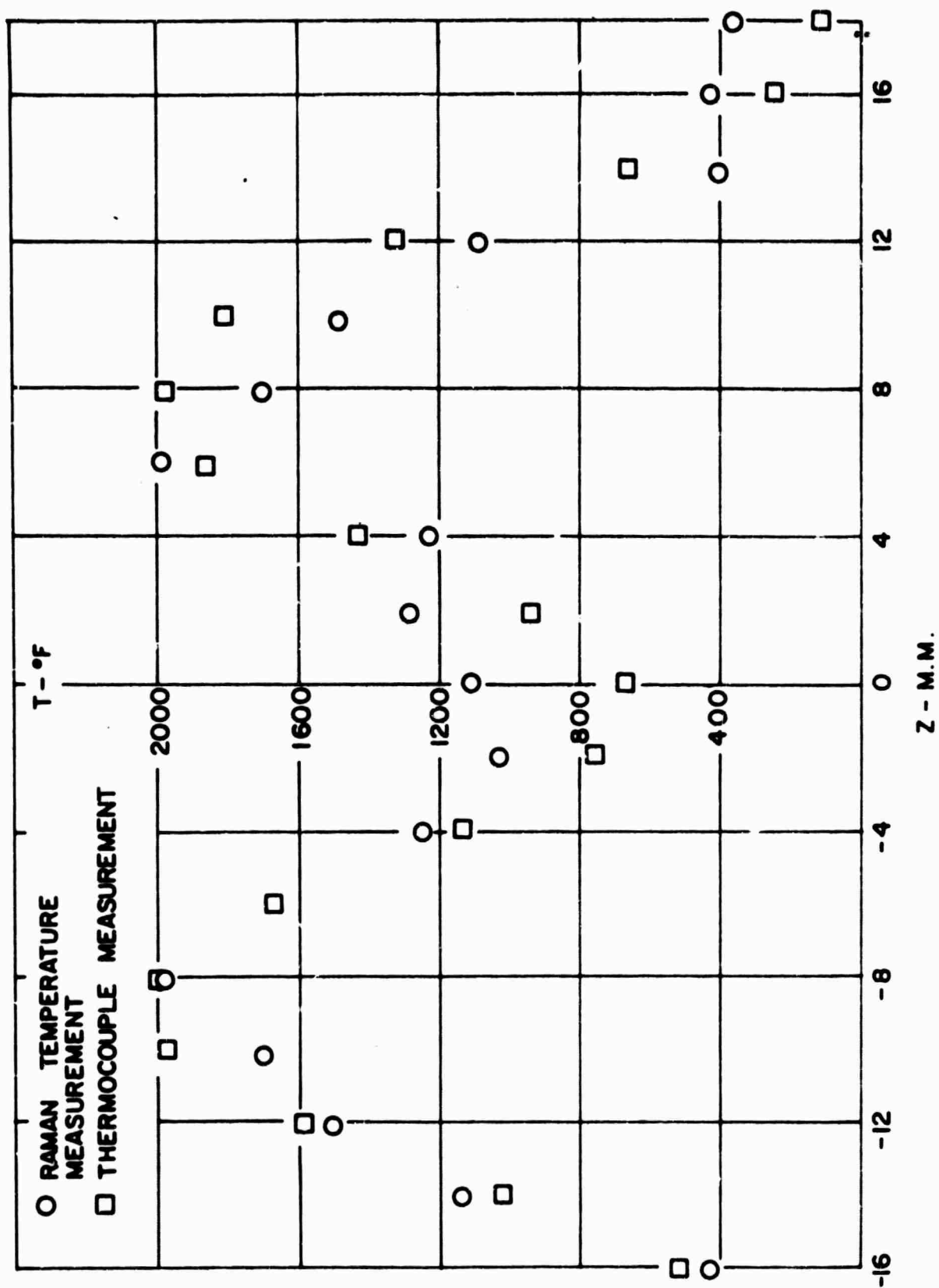FIG. 7   CO₂   CONCENTRATION — x / D = 20
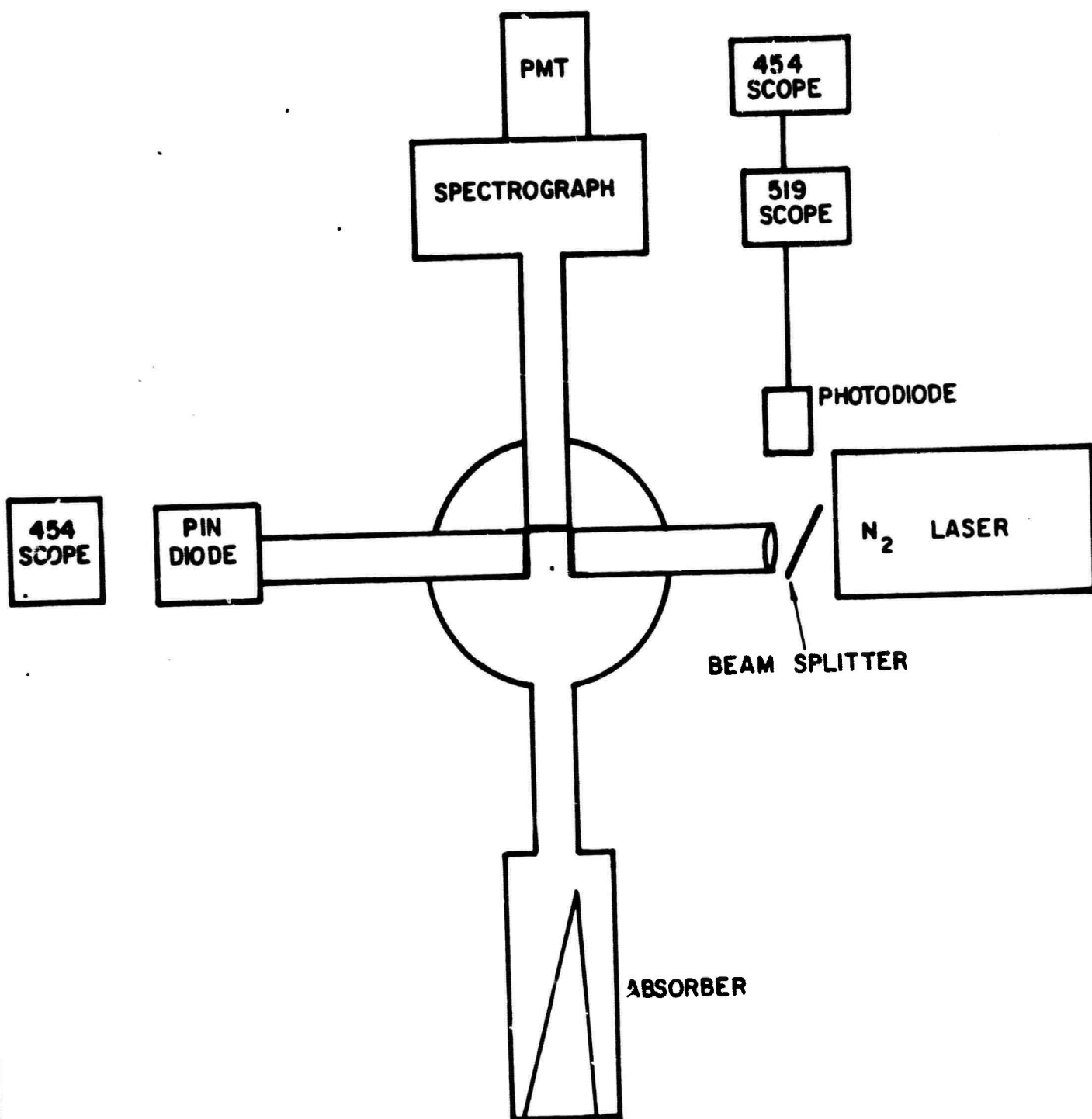
FIG. 8 TEMPERATURE PROFILE IN A METHANE CO₂ FLAME

23

FiG. 9 APPARATUS FOR RESONANT RAMAN
SCATTERING EXPERIMENTS